

STUDIES OF FISSION-YIELD MODELS *

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We study further a recent model for fission-fragment yield distributions based on Brownian shape motion on 5D potential-energy surfaces. Previously it was shown that this model describes well the transition between symmetric and asymmetric fission in the light Th region; here we study this transition near ^{258}Fm and compare to scission-type yield models. We also study the impact of the relative density of grid points in the different shape coordinates. Although extreme changes in grid spacing affect the calculated yields to some degree, we find that the full 5D model with our original grid choice is remarkably robust and that it is therefore suitable for applications, for example fission yields relevant for fission recycling in the r-process and its termination by fission.

Keywords: Fission yields, Brownian motion.

1. Introduction

In a recent paper¹ Randrup and collaborator introduced a highly accurate method for calculating fission-fragment yields at energies above the barrier based on Brownian shape motion (BSM) on 5D potential-energy surfaces. This method allows a fission yield distribution for a specific energy to be calculated on a single CPU in minutes to hours. For full specification of the model we refer to Refs.^{1,2} Here we benchmark the model further and implement an improved level-density model.

2. Results

We perform three investigations: (1) effect of semi-microscopic level density, (2) yield asymmetry in the ^{258}Fm region, and (3) effect of drastic changes in grid-point spacing. Additional benchmarking is in Ref.³

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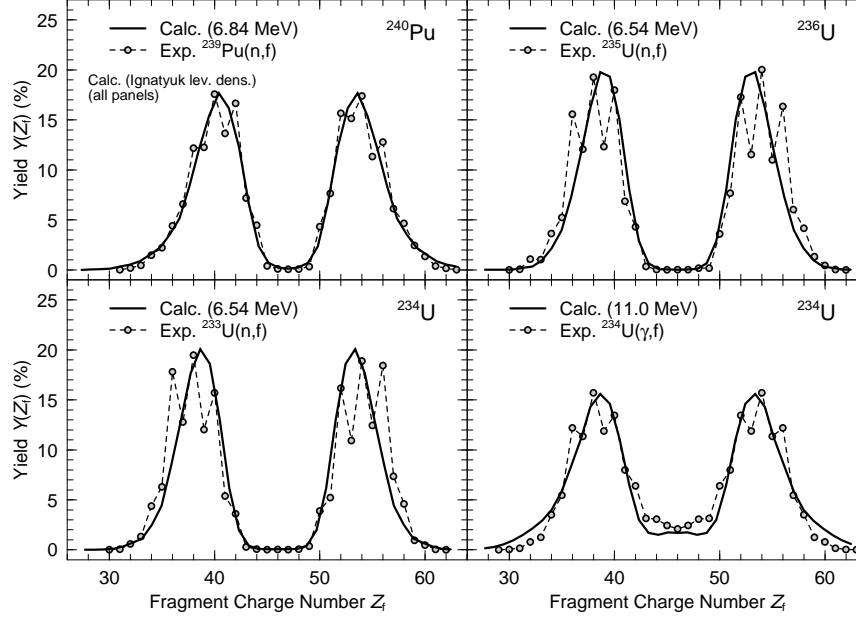


Fig. 1. Experimental yields and calculations with a semi-microscopic level density. We obtain a stronger energy dependence in the symmetric valley area than Ref.³ because as candidate neighbour points we use the 242 points on the 5D hypercube, Ref.³ uses the 10 points on the coordinate axes. Our choice leads to scission in fewer steps.

2.1. Level-density parameter

Relative to the model implemented in¹ we have introduced a level density-parameter a_{mic} that takes into account the effects of variation in single-particle level structure on the level density through the level-density parameter a_{mic} . Following Ignatyuk⁴ we write

$$a_{\text{mic}} = a_{\text{mac}} \left\{ 1 + \left[1 - \exp \left(-\frac{E^*}{E_{\text{damp}}} \right) \right] \frac{E_{\text{mic}}(Q_2, d, \epsilon_{f1}, \epsilon_{f2}, \alpha)}{E^*} \right\} \quad (1)$$

The parameters are: macroscopic level density parameter $a_{\text{mac}} = A/E_1$ with $E_1 = 8$ MeV and damping range $E_{\text{damp}} = 18.5$ MeV. The shell-plus-pairing correction $E_{\text{mic}}(Q_2, d, \epsilon_{f1}, \epsilon_{f2}, \alpha)$ is calculated for the deformed shape corresponding to each grid point from calculated folded-Yukawa single-particle levels by use of Strutinsky's method. In Fig. 1 we show our standard Pu/U test suite and find excellent agreement with experiment. In particular we find that the energy dependence is now much improved (compare the (γ, f) reaction in panel four in Fig. 1 with the corresponding result in Ref.¹

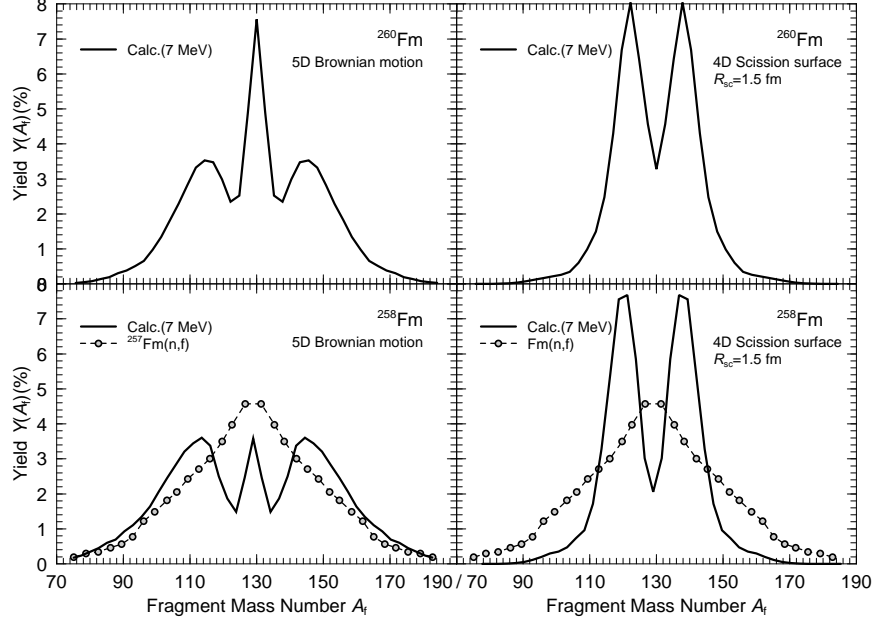


Fig. 2. Yields for ^{258}Fm and ^{260}Fm . Experimental data exist only for ^{258}Fm . The BSM model reproduces well the sharp evolution towards symmetry at and above ^{258}Fm , the scission model much less so.

2.2. Heavy *Fm* region and scission models

In many scission models^{5,6} it is assumed that the yield corresponds to thermal equilibrium on a scission surface. Thus, in point i we have

$$Y_i(E^*) \approx \rho(E^*) = \exp(2\sqrt{a(E^* - E_{\text{pot}}(Q_2, d, \epsilon_{f1}, \epsilon_{f2}, \alpha))}) \quad (2)$$

Previous studies have described the scission surface in a crude, non-obvious fashion in a low-dimensional deformation space as an object consisting of relatively few points. In contrast, we define a scission surface as a 4D object, on which the 5 shape coordinates vary smoothly from grid-point to grid-point. We start by defining a neck radius r_{sci} corresponding to scission. Next, we label each point in our 5D space +1 if its neck radius is larger than r_{sci} and -1 if it is smaller. Any point labeled +1 which is next to a point labeled -1 is defined as a scission-surface point. Consequently our scission surfaces consist of more than 100 000 points. In each grid point the unnormalized yield is calculated by use of Eq. 2. We obtain the normalized charge-yield curve by carrying out the proper summations and normaliza-

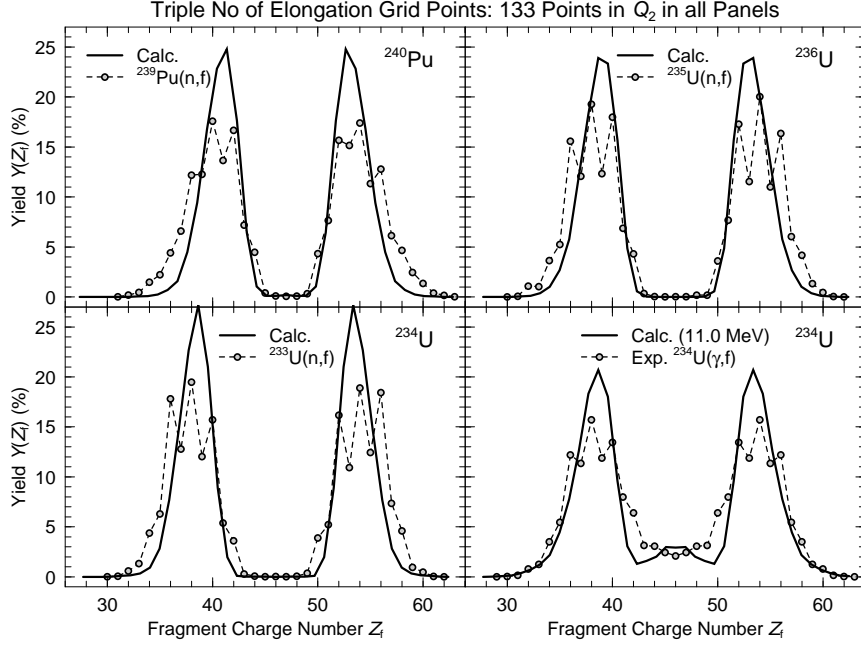


Fig. 3. Yields based on a potential energy with 3 times denser spacing of grid points in the Q_2 variable than our normal, preferred surface. Some narrowing of the distributions is observed. However, the excellent descriptions of (1) the varying width of the symmetric valley and (2) the energy dependence of the symmetric yield are remarkably robust.

tions. In Fig. 2 we show calculated yields in a BSM 5D model (our model of choice) and the above scission model for ^{258}Fm and ^{260}Fm .

2.3. Effect of grid-point spacing

By interpolation we have generated potential-energy surfaces that between the original Q_2 grid points have 2 additional points, effectively spacing the grid points three times denser in the fission (Q_2) direction. The calculated yields are displayed in Fig. 3. Some effect of this extreme change in grid-point spacing is seen. To make the results invariant to grid-point spacing we have calculated the overlap between a current point and its neighbor points throughout the grid. The next step (in progress) is to introduce a sampling probability that depends appropriately on the degree of overlap.

3. Conclusions

We have here and elsewhere^{1,3} shown the high accuracy with which the BSM model describes fission yields, including the transitions between symmetric and asymmetric yield in the $^{220-230}\text{Th}$ and ^{258}Fm regions. Although there is some dependence on the relative number of grid points in the five shape coordinates, see Fig. 3, we find that even under rather extreme changes the results are fairly robust. Clearly the number of grid points in the elongation direction Q_2 relative to the other shape variables introduces implicitly a time-scale of fission. However, it is a remarkable discovery that we obtain such robust results in a model whose specification took no account of fission yields. The calculated potential energy must therefore be highly realistic and further studies hold promise of new insights into the nature of the fission process.

An advantage of the method that cannot be overstated, is that a yield can be obtained in minutes to hours on a single CPU once the 5D potential energy is calculated. We have such surfaces calculated between the proton and neutron drip lines for all 5254 nuclides in the range $170 < A \leq 330$. Therefore the approach can immediately be used to calculate yield data bases for fission relevant to r-process modeling.

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